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A COMPARISON OF POLE POSITIONS DERIVED FROM GPS SATELLITE AND N--ETC(U)
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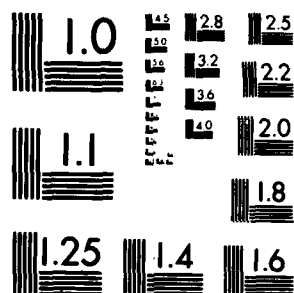
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The observation of the motion of the Earth's spin axis with respect to the crust has been done continuously since the latter part of 1899 by the International Latitude Service. With the advent of new technologies, new determinations of polar motion have been possible. Doppler tracking of the Navy Navigation Satellites has provided estimates of the polar motion on a permanent basis since 1969. Currently, these estimates are done at the Defense Mapping Agency and are distributed to several agencies including the Bureau International de l'Heure (BIH), which has the responsibility of centralizing polar motion data. The

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**A COMPARISON OF POLE POSITIONS DERIVED FROM GPS
SATELLITE AND NAVY NAVIGATION SATELLITE OBSERVATIONS**

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ABSTRACT

The observation of the motion of the Earth's spin axis with respect to the crust has been done continuously since the latter part of 1899 by the International Latitude Service. With the advent of new technologies, new determinations of polar motion have been possible. Doppler tracking of the Navy Navigation Satellites has provided estimates of the polar motion on a permanent basis since 1969. Currently, these estimates are done at the Defense Mapping Agency and are distributed to several agencies including the Bureau International de l'Heure (BIH), which is the responsibility of centralizing polar motion data. The Global Positioning System (GPS) is a new navigation satellite system which will eventually replace the existing Navy Navigation Satellite System. As a byproduct of the orbit estimation process for the GPS satellites, values for the position of the pole are determined. In this paper the two different methods for computing the pole's position from satellite observations are described. The most recent results from each method are compared to each other and to the standard BIH values.

INTRODUCTION

Since the late nineteenth century, it has been recognized that the instantaneous spin axis of the Earth moves with respect to the geographic pole of the Earth's crust. This "polar motion" was predicted by Euler in 1752, but was not conclusively observed until K nstner's work in 1884-86. The International Latitude Service (ILS) was established in 1899 to continuously monitor the motion of the pole by making systematic determinations of latitude.

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The basic idea was to make visual zenith telescope observations of stars at observatories on a common parallel ($39^{\circ}08' \text{ N}$) at well-distributed longitudes using the same reduction procedures. The origin, from which ILS polar motion is measured, is called the Conventional International Origin (CIO). The CIO pole, which is defined by the mean latitude of the five ILS observatories, is the mean position of the true celestial pole from 1900 to 1905.

With the development of new astrometric instruments during the 1950s and their use at the national observatories, it was decided that latitude measurements made at stations outside the ILS should be incorporated for polar motion determination. Therefore, the ILS was reorganized into the International Polar Monitoring Service (IPMS) in 1962 with the charter of deriving polar motion from latitude and universal time data of all astronomical instruments.

The Bureau International de l'Heure (BIH) was created in 1912 to unify time by publishing the time of emission (in universal time) of radio time signals. With the advent of atomic time standards in 1955 and the need to account for polar motion in a timely manner for UT1 determination, the BIH began to determine its own set of coordinates of the pole from latitude data supplied by participating observatories. Until 1972 the BIH used only the same data as the IPMS so a complete overlap of functions with the IPMS existed. Since 1972, pole positions based on Doppler observations of the Navy Navigation Satellites have been incorporated into the BIH global solution. A detailed description of the method used by the BIH for polar motion determination was given by Feissel (1980).

Research at the Naval Weapons Laboratory by Anderle and Beuglass (1970) demonstrated that it was possible to use Doppler observations of Navy Navigation Satellites to compute pole positions. Doppler solutions of pole position have been distributed by the Dahlgren Polar Monitoring Service since 1969. The pole positions are a byproduct of the orbit computation process. Hence, when the responsibility of computing the Navy Navigation Satellite orbits was transferred to the Defense Mapping Agency (DMA) in 1975, the derivation of pole position was also carried out by DMA. The DMA-HTC Polar Monitoring Service (DPMS) reports are distributed by the Hydrographic/Topographic Center of DMA to users on a weekly or monthly basis and provided to the U. S. Naval Observatory on a weekly basis for inclusion in their Time Service Announcement, Series 7. Additional history and information on the polar motion services has been given by Guinot (1978).

COMPUTATIONAL METHODS FOR DOPPLER DATA

The pole determination method utilized by DMA is the method adopted by the Naval Surface Weapons Center (NSWC) in August 1971. The brief description of the method that follows is taken from the detailed description of the observational procedures, and the data reduction techniques given by Anderle (1973).

Doppler observations are made daily by a network of approximately 20 worldwide tracking stations controlled by DMA and by a network of 4 U. S. tracking stations controlled by the Navy Astronautics Group. Sometimes these observations are supplemented by tracking data from portable Doppler receivers. Two types of Doppler data are processed: "sampled Doppler data" which gives a value of the Doppler frequency every 4 seconds and "continuous count integrated Doppler (CCID) data" which gives a value of range difference each 10 to 20 seconds. All observations taken in a 48-hour period are processed by the CELEST (O'Toole, 1976) computer program.

Extensive preprocessing is performed on the Doppler data. Data are rejected if transmission errors have garbled any characters or formats or if unusual time gaps appear in the series of observations. Time corrections are then applied to the data and the data are filtered to detect gross errors. A least-squares solution for a modified station position for each pass is performed to linearize residuals for filtering purposes. Residuals for the modified station position are rejected if they are excessive. The process continues until no additional points are rejected. All passes of data are then combined and passes with excessive modified station position errors are rejected.

After the preprocessing of two day's worth of data is done, a least-squares solution is obtained which includes the 6 constants of orbital integration, a drag scaling factor for each day, a frequency and a tropospheric refraction scaling factor for each pass, the 2 components of the pole position, and the coordinates of any mobile observing station. The least-squares solution is based on differences between the observations and computed data which corresponds to a predicted satellite orbit. The initial conditions for the equations of motion come from the previous day's orbit fit. The integration scheme is a 12th-order Cowell with a one-minute stepsize. The mathematical model includes the Earth's gravitational field, atmospheric drag, solar radiation pressure, luni-solar gravity perturbations, and solid Earth tidal forces. The integration is done in the true-of-date system.

Two satellites are currently being tracked for precise ephemeris computations. The primary satellite is 1970-67A and the secondary satellite is 1967-92A. Approximately 140 passes of data are available for each satellite during the 48-hour time span. The current accuracy of the orbit determination as measured by the discontinuity in the ephemeris at the ends of each 48-hour fit and the root mean square of the residuals of the least squares adjustment is approximately 3 meters. This value agrees with the previous value quoted by Bowman and Leroy (1976).

The initial values for the polar motion parameters come from doing a least squares fit of the following function using the most recent 200 day's worth of calculated polar motion parameters.

$$f(t) = A + B \cos(\omega t) + C \sin(\omega t)$$

$$\omega = (2\pi/420) \text{ where } 420 = \text{Chandlerian period}$$

The results of carrying out separate fits for the x- and y-components of polar motion are used to predict new values for the next seven days.

ACCURACY OF DOPPLER POLE POSITIONS

Several investigators have examined the error sources associated with the Doppler results and the accuracy of the pole positions. Anderle (1973) discussed the early results and error sources. Oesterwinter (1979) has given a comprehensive review of Doppler results through 1977. Bowman and Leroy (1976) have performed a spectral analysis of the x- and y-components of pole position. Guinot (1979) has examined irregularities of the polar motion by comparing classical astrometry results to the DMA Doppler results. Gambis and Nouël (1980) have discussed the results of the MEDOC experiment which was an independent determination of pole position using Doppler data. Oesterwinter gives the standard deviation of the two-day solution with respect to the DPMS five-day mean as 40 centimeters and the standard deviation of the five-day mean (standard error) as 20 centimeters. Systematic errors are due to an inadequate knowledge of the gravity field and results are affected by atmospheric drag variations and changes in the station network.

The accuracy of the pole positions as reflected in the standard deviations of the two-day solutions with respect to the five-day means had been steadily increasing since 1967. However, the results for 1981 show a much larger scatter. The average values for the x- and y-components were 84 (0.027) and 64 (0.021) centimeters, respectively. The larger scatter in the determinations of pole position is correlated with high values for the atmospheric drag parameters.

NAVSTAR GLOBAL POSITIONING SYSTEM

The NAVSTAR Global Positioning System (GPS) is an advanced satellite-based navigation system currently under development by the Department of Defense. It will ultimately provide position and timing information accuracies on the order of meters and tens of nanoseconds continuously on a worldwide basis to a variety of users. The GPS consists of three major segments: the Space Segment, the Control Segment, and the User Segment.

The Space Segment contains the satellites. In its operational configuration the GPS satellite constellation will consist of 18 Navigation Development Satellites (NDSs) in circular, 12-hour orbits (20,200 kilometers) with inclinations of 55 degrees. The NDSs transmit coded signals at 1575.42 and 1227.6 MHz which consist of a precise navigation signal, a course navigation signal, and data such as satellite ephemerides, satellite clock bias information, and atmospheric propagation correction data. Currently, the useful GPS

satellite constellation consists of 4 satellites in circular, 12-hour orbits with inclinations of 63 degrees.

The Control Segment contains four monitor stations, an upload station, and a Master Control Station (MCS). It is responsible for tracking the satellites, preparing the navigation data for the satellites, and uploading the data into a satellite navigation processor. This process is done at least once per day.

The User Segment contains the various user equipment sets which demodulate the navigation data sent by the satellites and process them to determine the user's three-dimensional position, velocity, and system time. Examples of typical user performance are given by Henderson and Strada (1980). Additional information on the principle of operation and system characteristics of GPS are given by Milliken and Zoller (1978).

The GPS program is currently in the full-scale development and system test phase. In two years the decision whether to enter the production and development phase leading to full GPS capability will be made. Because the program is in the test phase, it seems appropriate to examine whether useful information can be obtained for pole position as a byproduct of the orbit computation process.

COMPUTATIONAL METHODS FOR GPS DATA

The MCS at Vandenberg AFB, California, completely controls the operation of the Control Segment of the GPS. The primary function of the MCS is to provide the NDSs with precise navigation data. Tracking data consisting of pseudoranges (true slant ranges from the user to the satellite plus propagation delays and time biases) and delta pseudoranges (integrated Doppler) are collected by the monitor stations and sent to the MCS for processing. The data are preprocessed, smoothed, and then run through a Kalman filter to estimate the NDS ephemerides and clock behavior so that predicted ephemerides can be uploaded to the satellites.

The MCS ephemeris determination processing is summarized functionally in Fig. 1. The monitor stations collect the following data for each satellite in view (nominally every 6 seconds): L_1 pseudorange measurement, L_1 - L_2 pseudorange difference measurement, and delta pseudorange (integrated Doppler) on L_1 . In addition to the measurement data, meteorological and satellite (SV) navigation data are sent to the MCS. The preprocessor (PREP) unpacks and scales the measurement data, edits bad data, corrects the measurement time tag, and corrects the measurements for antenna phase center offsets, ionospheric delays, tropospheric effects, relativistic effects, and Earth rotation during signal transit. The smoother (SMOOTH) processes all measurements contained within the 15 minute Kalman filter cycle for each satellite-monitor station pair. Wild points are edited. The remaining pseudorange and delta pseudorange measurements are fit by least squares to a polynomial and 1 smoothed pseudorange residual and 1 smoothed delta pseudorange residual with

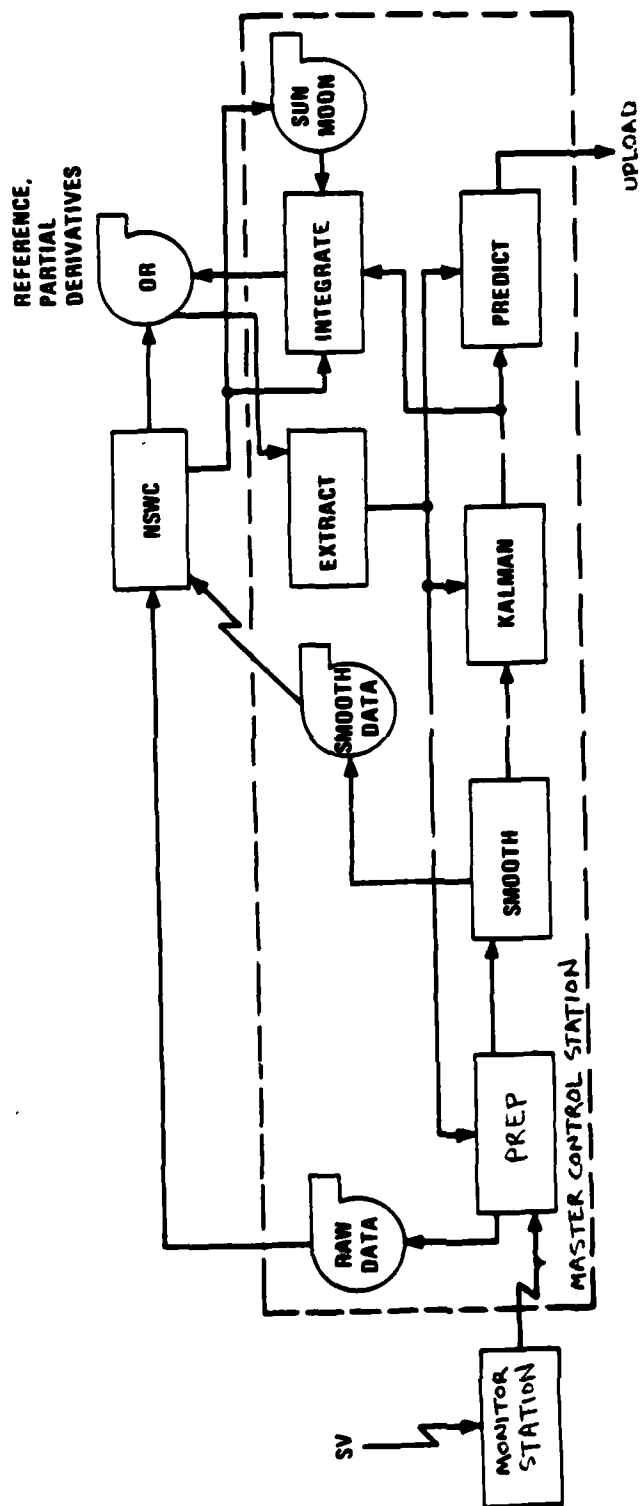


Figure 1.—Functional Block Diagram of the MCS Ephemeris Determination Processing.

appropriate statistics are sent on to the Kalman filter (KALMAN). The Kalman filter processes the smoothed measurements to estimate NDS position and velocity residuals, NDS solar radiation pressure model scaling parameter residuals, NDS clock offset states, monitor station clock offset states, tropospheric delay residual states, and polar wander residual states. KALMAN is a square-root, sequential Kalman filter process. The predictor (PREDICT) uses the most recent Kalman estimates of the residuals to predict the Earth-fixed Cartesian coordinates of the satellite position which can then be uploaded to the satellite. The Kalman filter implementation requires a reference trajectory which can be generated by an integrator (INTEGRATE) or by the Naval Surface Weapons Center (NSWC). The relevant portions of the reference trajectory needed for PREP, KALMAN, and PREDICT are obtained by the extractor (EXTRACT).

The reference trajectory provides the initial estimate of the satellite trajectory about which the perturbations are computed by the Kalman filter and the partial derivatives which are also needed by the Kalman filter. The smoothed tracking data are transmitted to NSWC each day. A least-squares batch fit using range difference data is used to generate the reference ephemerides every two weeks at NSWC. Predicted values of the pole position are also included on the reference tape. These values are obtained by fitting a function similar to the Doppler function but also including a sine and a cosine term with an annual period. A Chandler period of 435 days is used and the most recent 435 day's worth of BIH data are used for the fit (Carr, 1981). For the NDSs on atomic standards, typical errors for a two-week prediction versus the fit span are 5 meters root-mean-square (rms) in the radial and normal directions and 50 meters rms in the tangential direction for the reference trajectories.

When the Kalman filter was designed at the MCS, it was decided to not describe the dynamics of the polar wander states. Therefore, the states are constant and propagate in time via the identity matrix. The Kalman estimates of these states (based on ranging measurements) will change with time, but epoch updates (updating the reference values) will not change the total state. The following equation describes the epoch update process for polar wander.

$$\hat{PW}_{cn} = PW_o + \hat{PW}_{co} - PW_n$$

where PW_o = old reference (NSWC) value of polar wander

PW_n = new reference (NSWC) value of polar wander

\hat{PW}_{co} = current estimate of polar wander residual state
relative to the old reference value

\hat{PW}_{cn} = current estimate of polar wander residual state
relative to the new reference value

The first two terms on the right-hand side of the equation represent

the total polar wander state. The process noise matrix describes the estimated uncertainty and correlations of the Kalman filter states due to unmodeled effects or modeling errors. The process noise matrix for the polar wander states assumes that the residual states behave like stationary independent white noise random processes over the periods between successive NSWC reference values of polar wander. Nominal values for the process noise correspond to a position uncertainty of 0.7 meter over a period of a day.

The values of the pole position based on MCS Kalman filter processing were obtained from a dump of the Kalman estimate file just before the first scheduled uploads of the NDSs each day. As long as the current estimate of the polar wander residual state is not reset to zero, the total polar wander state is independent of the reference value supplied by NSWC.

Additional information on the operation of the MCS and the Control Segment has been given by Russell and Schaibly (1978) and Varnum (1982).

ACCURACY OF GPS POLE POSITIONS

Anderle, Beuglass, and Carr (1981) have computed pole position and Earth rotation for six 7-day spans of GPS tracking data observed during the MERIT short campaign. They concluded that both standard errors and consistency of the results were somewhat worse than those obtained from the Navy Navigation Satellite data. They give standard deviations of the x- and y-components ranging from 26 to 85 centimeters depending on the assumed uncertainty of station bias and frequency.

The standard deviations of the daily solutions with respect to the five-day means are quite small. The average value for both the x- and the y-component is 6 (0.002) centimeters. These small values are indicative of the constraints on the solution in the MCS Kalman filter.

COMPARISON OF RESULTS

The pole paths computed by Doppler observations of the Navy Navigation Satellites (DMA), by MCS Kalman filter processing of NDS data (MCS), and by the BIH are shown in Fig. 2. The DMA data, the MCS data, and the BIH data are plotted as dots, pluses, and circles, respectively. The scatter in the DMA data with respect to the BIH is quite large. In addition the DMA data appear to be systematically deviating from the BIH in the final part of the year. The MCS data show a significant bias with respect to the BIH and the DMA data for most of the year. The BIH data are the Circular D final values. Graphs of the components of pole position as a function of time are shown in Figures 3 and 4. The MCS data fit the BIH values better than DMA data for the x-component while just the opposite is true for the y-component. Residuals of the different estimates of pole position are given in Figures 5 and 6. Table 1 presents a

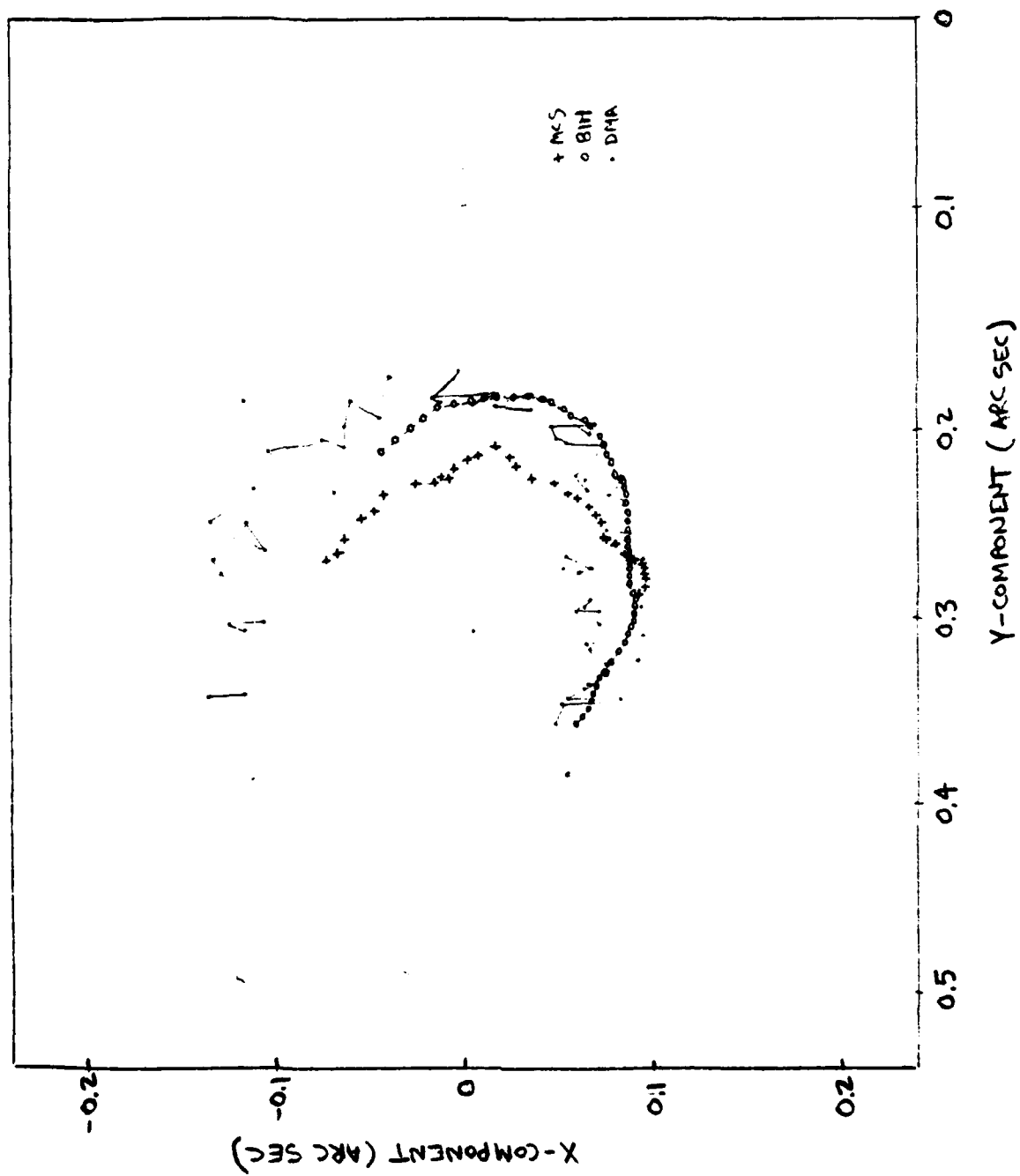


Figure 2. Pole Path for 1981.

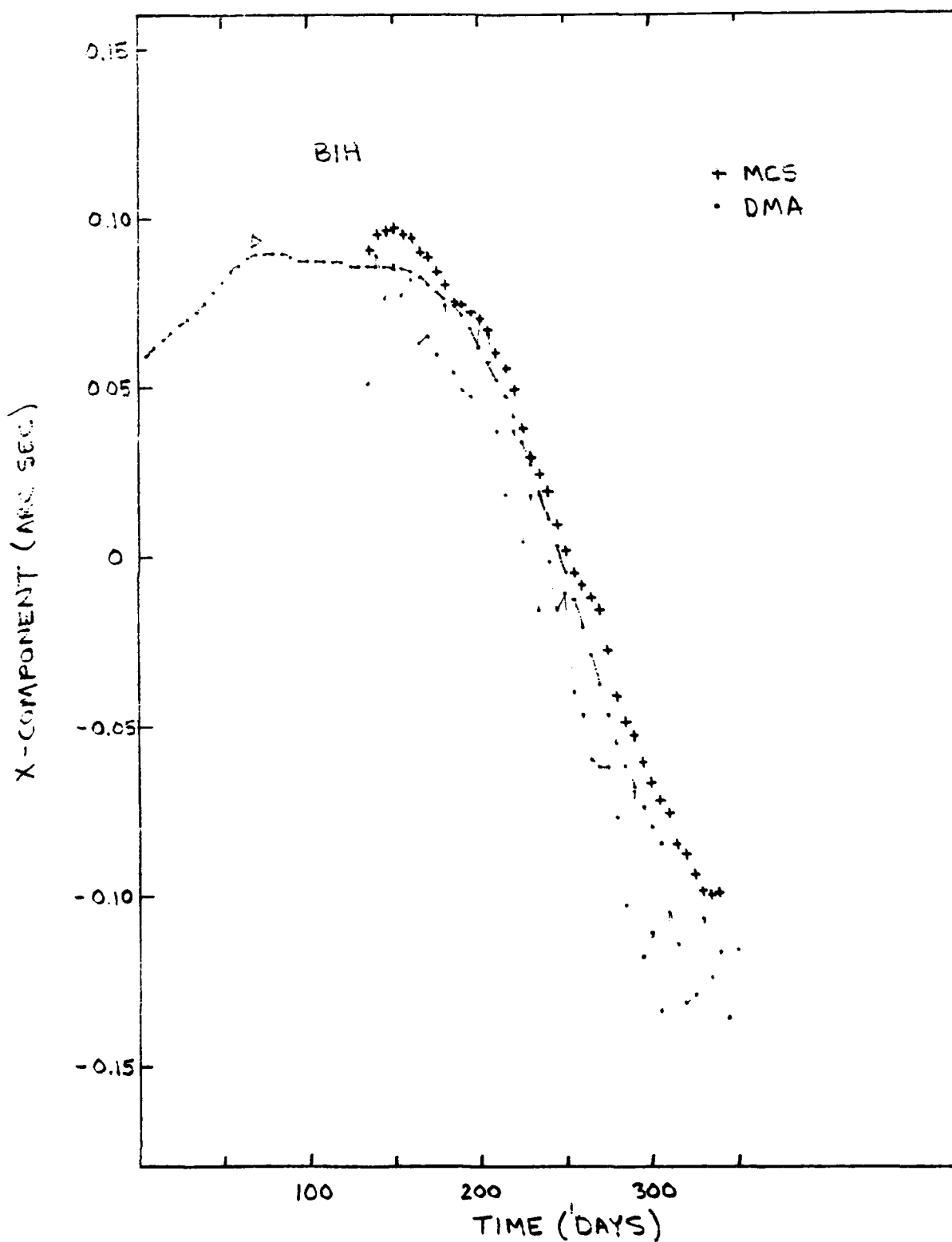


FIGURE 3. X-COMPONENT OF POLE POSITION FOR 1981.

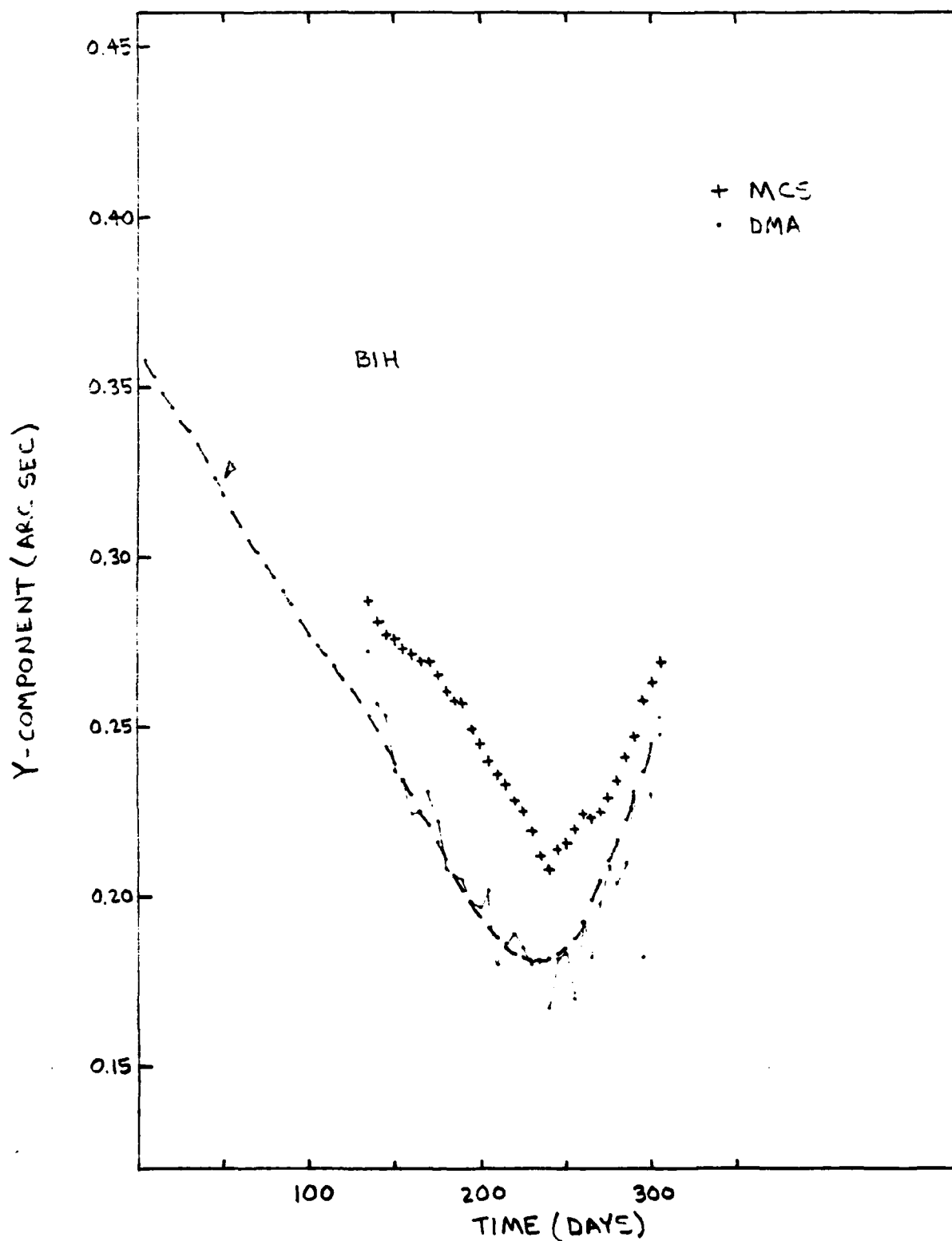


FIGURE 4. Y-COMPONENT OF POLE POSITION FOR 1981.

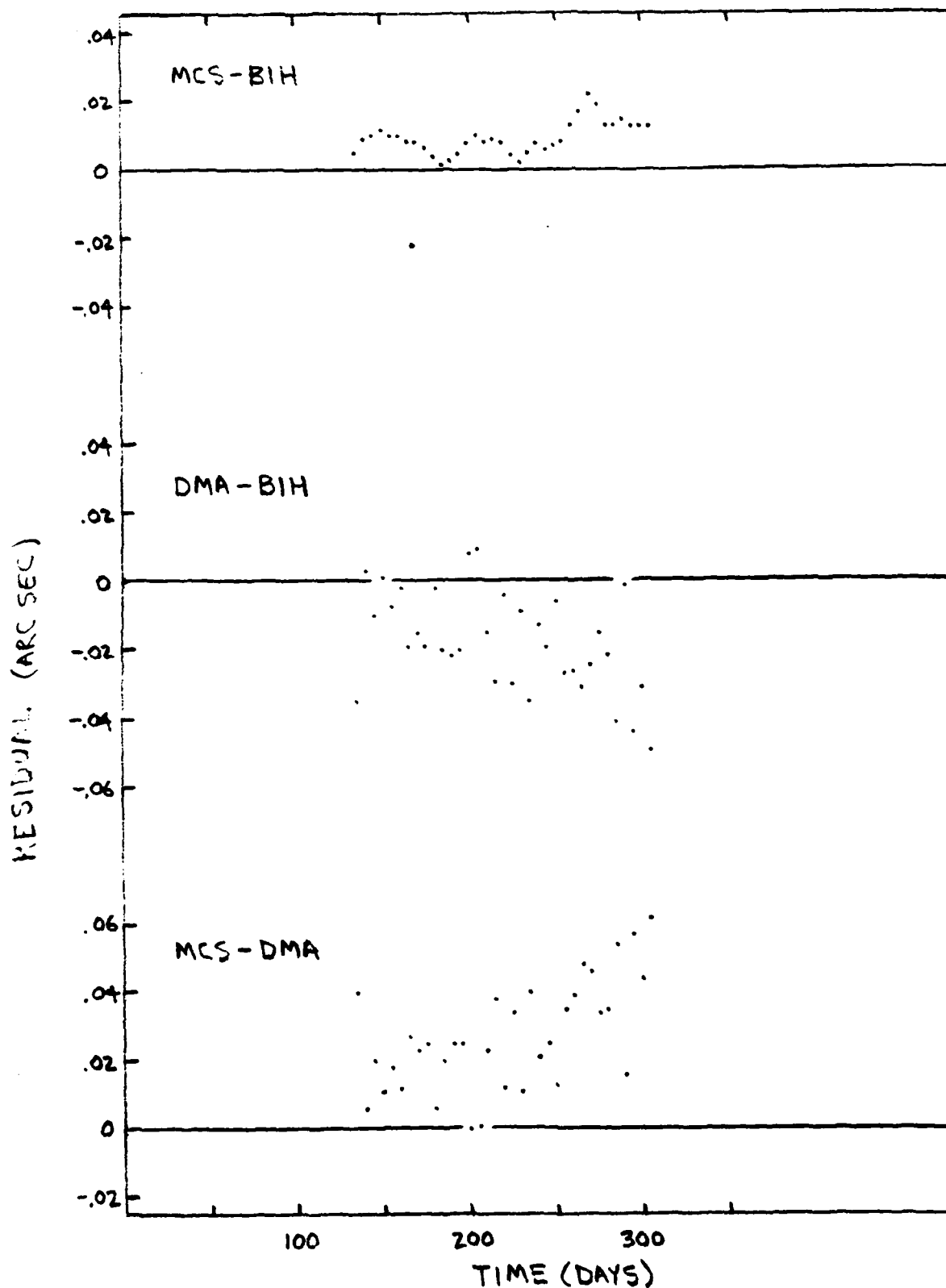


Figure 5. - Residuals of Estimates of the X-component of Pole Position for 1981.

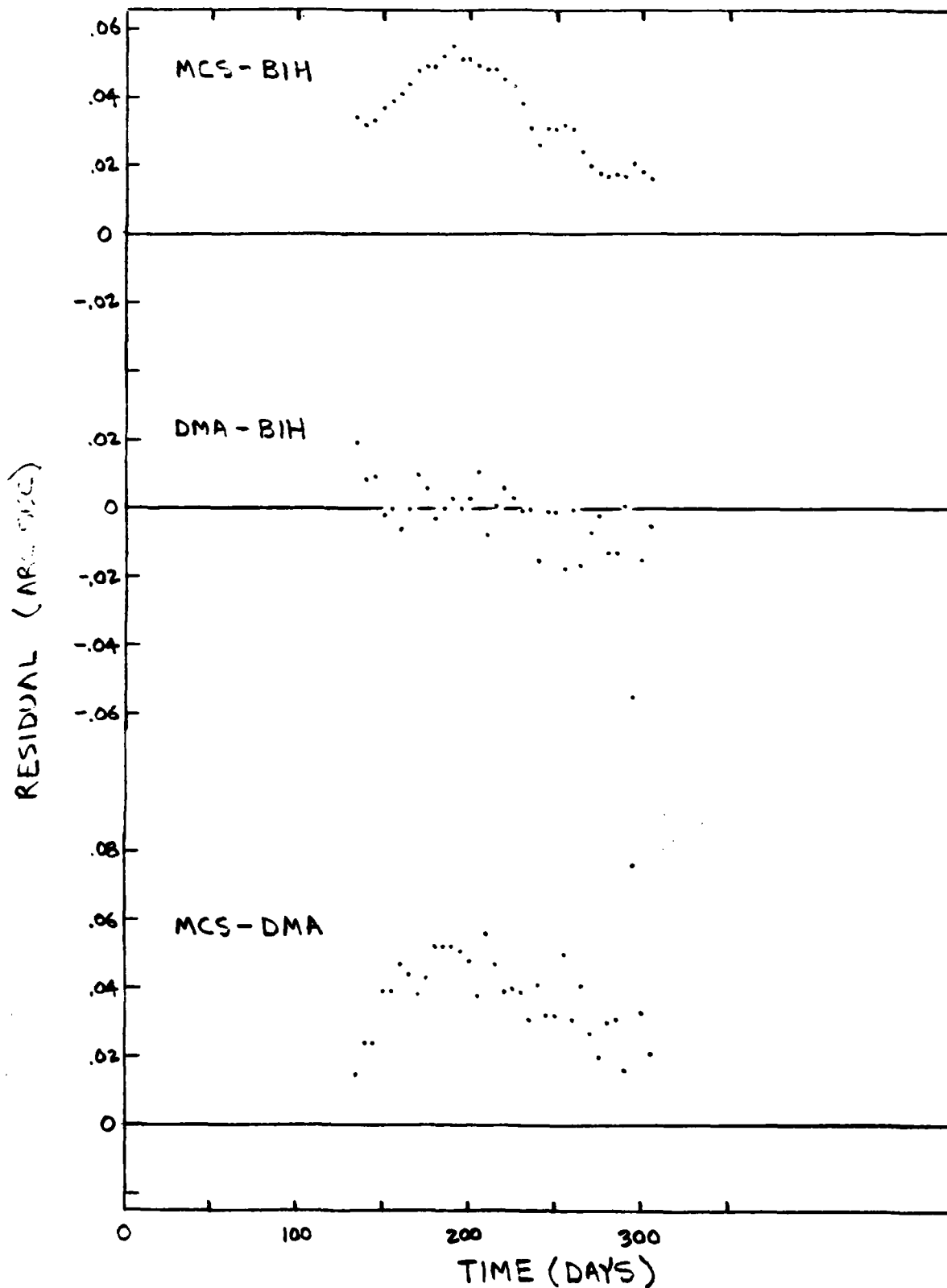


Figure 6. - Residuals of Estimates of the Y-component of Pole Position for 1981.

summary of the root-mean-square differences of the residuals given in Figures 5 and 6.

Pole Position Differences (arc sec)						
	MCS - BIH		DMA - BIH		MCS - DMA	
	<u>X</u>	<u>Y</u>	<u>X</u>	<u>Y</u>	<u>X</u>	<u>Y</u>
mean difference	.009	.035	-.018	-.003	.027	.038
std. deviation	.005	.012	.015	.012	.016	.013
std. error	.001	.002	.003	.002	.003	.002

TABLE 1. COMPARISON OF MEAN ESTIMATES OF COORDINATES OF THE POLE
SUMMARY

Pole positions have been computed as a byproduct of the orbit estimation process for the GPS satellites at the Master Control Station (MCS). The precision of the daily values indicates an uncertainty of 0.002 or 6 centimeters. However, systematic errors are apparent in the results. A bias of about 1 meter exists between the MCS pole positions and the positions given by the Bureau International de l'Heure (BIH) for the y-component. When the MCS results are compared to the BIH values, the scatter about the mean difference is much smaller than for the DMA pole positions. In addition to the systematic errors, some periodicities may exist in the data but the data span of MCS values is still too short to do a comprehensive analysis.

Preliminary analysis of MCS pole positions has given encouraging results. However, more data need to be analyzed and additional studies need to be completed before definitive statements can be made about the causes of the biases and the appropriateness of including these data in a global solution for polar motion.

ACKNOWLEDGMENTS

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